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**Progress Towards a Muonium Gravity Experiment**

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The gravitational acceleration of antimatter,  $\bar{g}$ , has yet to be directly measured but could change our understanding of gravity, the Universe, and the possibility of a fifth force. Three avenues are apparent for such a measurement: antihydrogen, positronium, and muonium, the last requiring a precision atom interferometer and benefiting from a novel muonium beam under development. The interferometer and its few-picometer alignment and calibration systems appear to be feasible. With 100 nm grating pitch, measurements of  $\bar{g}$  to 10%, 1%, or better can be envisioned. This could constitute the first gravitational measurement of leptonic matter, of second-generation matter and, possibly, the first measurement of the gravitational acceleration of antimatter.

Despite many years of effort, experiments on antimatter gravity have yet to yield a statistically significant direct measurement. Such studies using antihydrogen and positronium are ongoing. We report here on progress towards a measurement using muonium.

*Indirect* tests, based on the expected amounts of virtual antimatter in the nuclei of various elements, imply stringent limits on the gravitational acceleration,  $\bar{g}$ , of antimatter on earth:  $\bar{g}/g - 1 < 10^{-7}$ .<sup>1a</sup> A *direct* test of the gravitational interaction of antimatter with matter seems desirable on quite general grounds<sup>2</sup> and is of interest whether viewed as a test of General Relativity or as a search for a fifth force. Candidate quantum gravity theories include the possibility of differing matter–antimatter and matter–matter forces;<sup>2b</sup> recent work<sup>3</sup> on gravity in the SME framework emphasizes the importance of second-generation measurements. The short

<sup>a</sup>The extent to which these limits apply to muonium is far from obvious.

<sup>b</sup>For example, suppressed scalar and vector terms may cancel in matter–matter interactions, but add in matter–antimatter ones.

lifetimes of second- and third-generation particles may make muons the only experimentally accessible avenue to gravity beyond the first generation.

Although most physicists expect the equivalence principle to hold for antimatter as well as for matter, theories in which this symmetry is *maximally* violated (i.e., in which antimatter “falls up”) are attracting increasing interest<sup>4c</sup> as potentially solving six great mysteries of cosmology (Why is the cosmic microwave background so isothermal? Why is the Universe so flat? Why are galactic rotation curves flat? What happened to the antimatter? Why does  $\Lambda = 0$  cosmology give the age of the Universe as younger than the oldest stars, and Type IA supernovae dimmer than predicted?), all without the need for cosmic inflation, dark matter, or dark energy.

We are developing a precision three-grating atom-beam interferometer for the measurement of  $\bar{g}$  using a slow muonium beam at Switzerland’s Paul Scherrer Institute (PSI).<sup>6</sup> The interferometer can measure the atoms’ gravitational deflection to a fraction of a nanometer, determining  $\bar{g}$  to a precision of 10% of  $g$  in a month of beam time (assuming a typical 30% overall efficiency). Additional time, intensity, or efficiency could permit a measurement to 1% or better. The RMS statistical precision is estimated as<sup>7</sup>  $\delta g = d/(2\pi C\sqrt{N}t^2)$ , where  $C = 0.1$  is the fringe contrast,  $N$  the number of events detected, and  $t$  the muonium transit time through the interferometer. A finer grating pitch  $d$  is helpful; we have chosen  $d = 100$  nm as a compromise between sensitivity and systematic error due to geometry variations over the  $\sim \text{cm}^2$  grating area. At the anticipated rate of  $10^5$  muonium atoms/s incident on the interferometer, the statistical measurement precision is about  $0.3g$  per  $\sqrt{N_d}$ , where  $N_d$  is the exposure time in days.

The monoenergetic muonium beam is under development at PSI;<sup>6</sup> a first test using an existing, thermal-muonium beam is also of interest and could potentially provide the first determination of the sign of  $\bar{g}$ . Interferometer development, including  $\text{Si}_3\text{N}_4$  grids nanofabricated using  $e$ -beam lithography and reactive-ion etching at the ANL Center for Nanoscale Materials, is underway using teams of IIT undergraduates and donated equipment and facility time.<sup>8</sup> A key challenge is the need to translate one grating vertically with at least 10 pm precision in order to scan the interference pattern. Most recently, using two semiconductor-laser tracking frequency gauges<sup>9</sup> (TFGs) we have demonstrated position measurement to  $\approx 3$  pm, with work ongoing to reduce residual noise. The 10 pm requirement is seen (Fig. 1) to imply a need for geometric stability over at least 0.3 s and calibration with X-rays

<sup>c</sup>See Ref. 5 for further references as well as a more detailed discussion of our experiment.

at least every 1000 s.

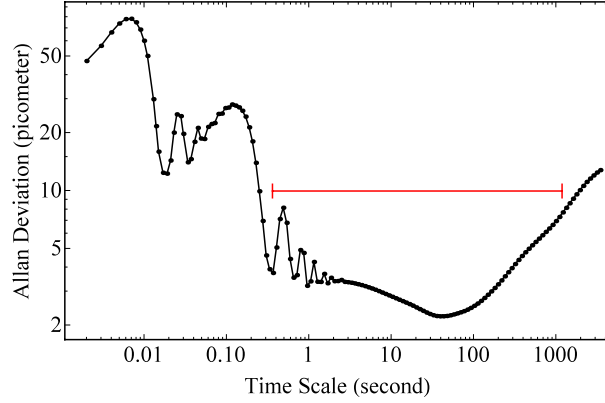


Fig. 1. Allan deviation vs. averaging time obtained at IIT for a two-TFG test showing  $\lesssim 3$  pm precision with one- to several-second averaging time. The bar at 10 pm (red online) shows the range of time scales over which the TFG measurement is useful.

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